Summary of Three Historical Studies of Soot in the Atmosphere and Snowpack in 1983, 1984 and 1986

Airborne Observations of Arctic Aerosol-IV:
Optical Properties of Arctic Haze

Clarke, A.D., R.J. Charlson and L.F. Radke
Geophysical Research Letters, 11, 405-408, 1984.

Soot in the Arctic Snowpack:
A Cause for Perturbations of Radiative Transfer

Clarke, A.D. and K.J. Noone.
Atmospheric Environment, 12, 1985

Soot Scavenging Measurements for Arctic Snowfall

Noone, K. J., A. D. Clarke
Atmospheric Environment, 22, 12, 2773, 1988.

In-Situ Measurements of the Aerosol Size Distributions, Physiochemistry and Light Absorption Properties of Arctic Haze

Clarke, A.D. , *Jour. of Atmos. Chem.*, 1989

AGASP 1 aircraft flights April 1983 and Snow Samples 1982-1983

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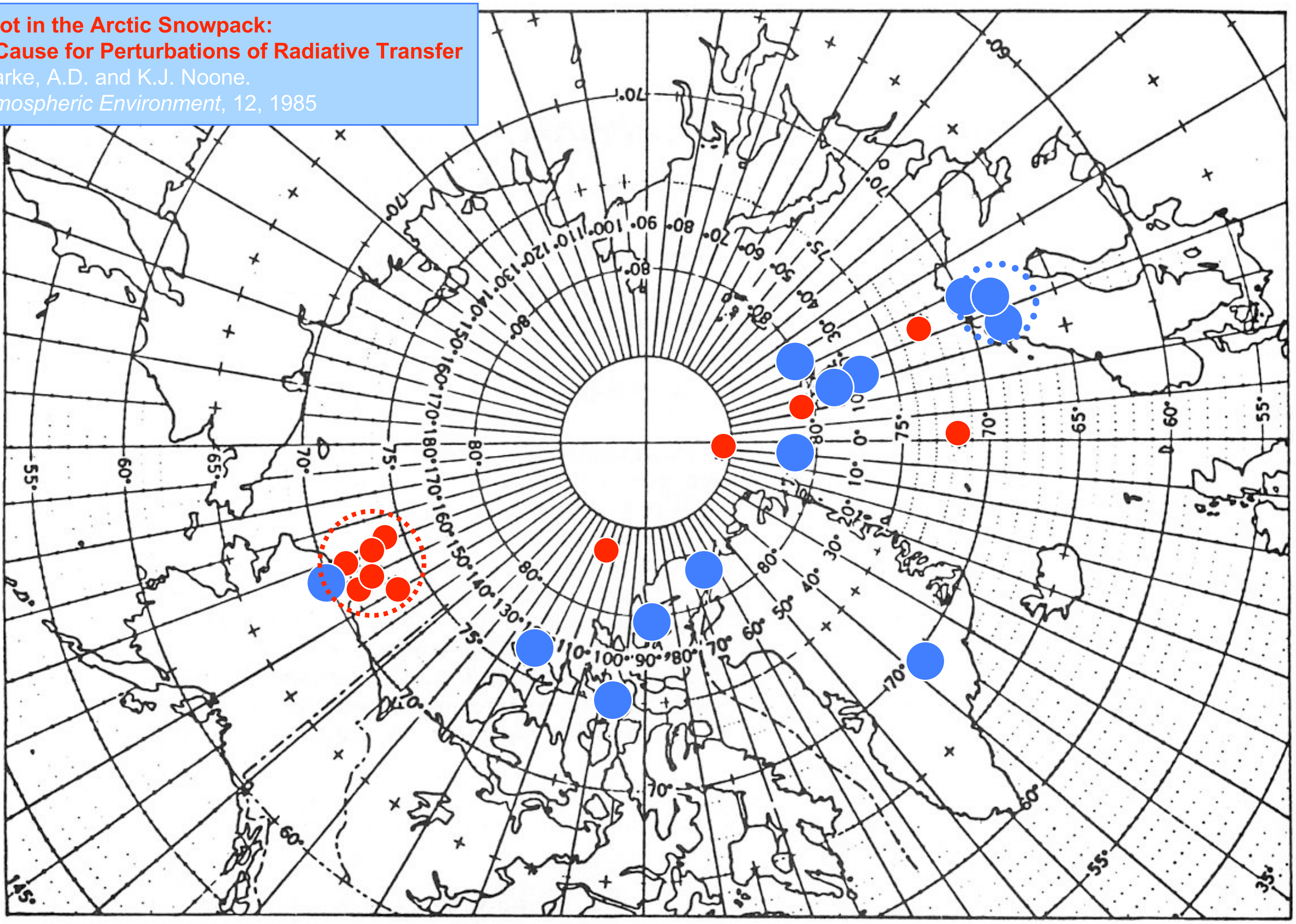

Fig. 1. Map of Arctic sampling locations for the University of Washington atmospheric ( ) aircraft samples and snowpack ( ) samples for 1983 and 1984.

1983

Barrow Based flights in April 1983
Scattering, Absorption, SSA

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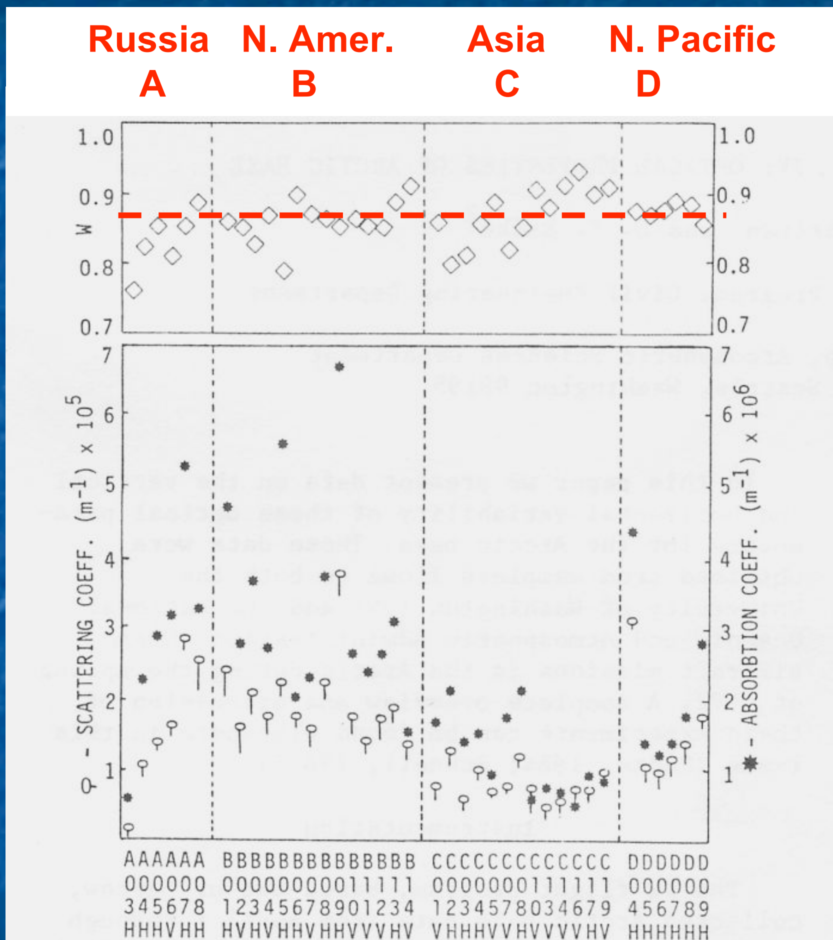

Fig 1. Time series of aerosol absorption coefficient (✱), scattering coefficient (⚲) and single scattering albedo (◇) for UW Arctic haze flights. See text for description of identifier label code and Table 1 for data description. Flagged data from Table 1 excluded.

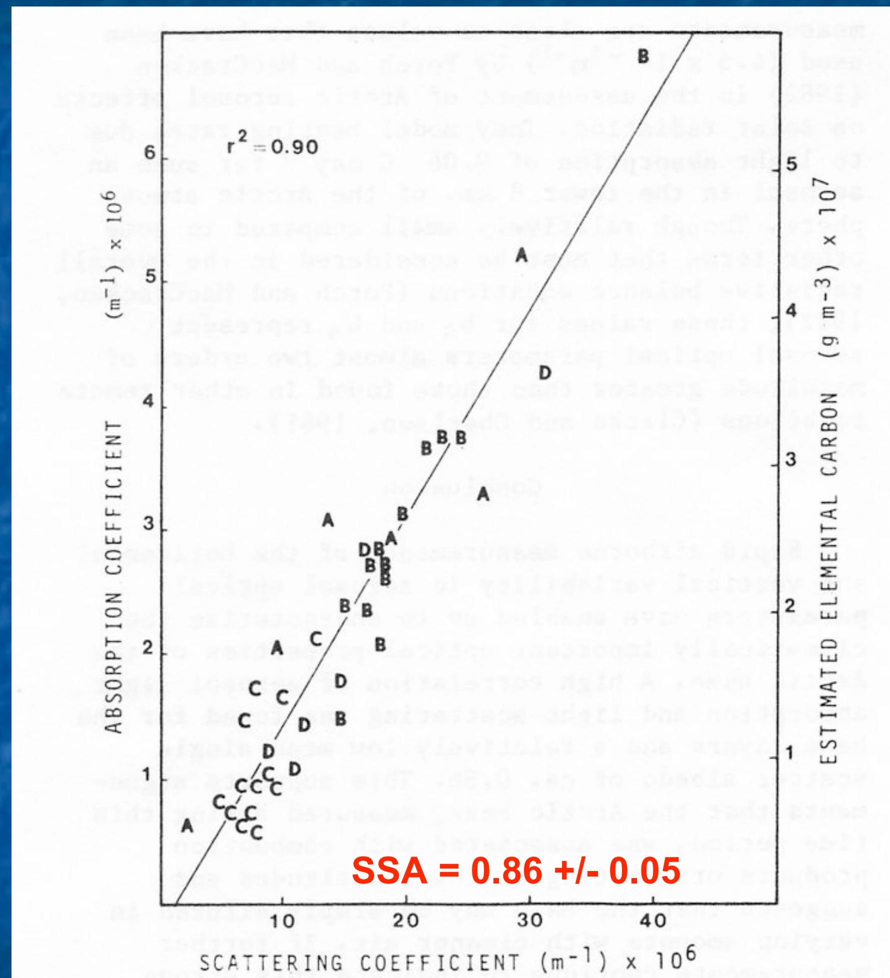

Fig 2. Plot of aerosol absorption coefficients vs. scattering coefficients for UW Artic haze flights including regression line. Flagged data from Table 1 are excluded and letter symbols refer to air mass types discussed in text.

BARROW, Alaska: Surface
March 27 –April 4, 1986

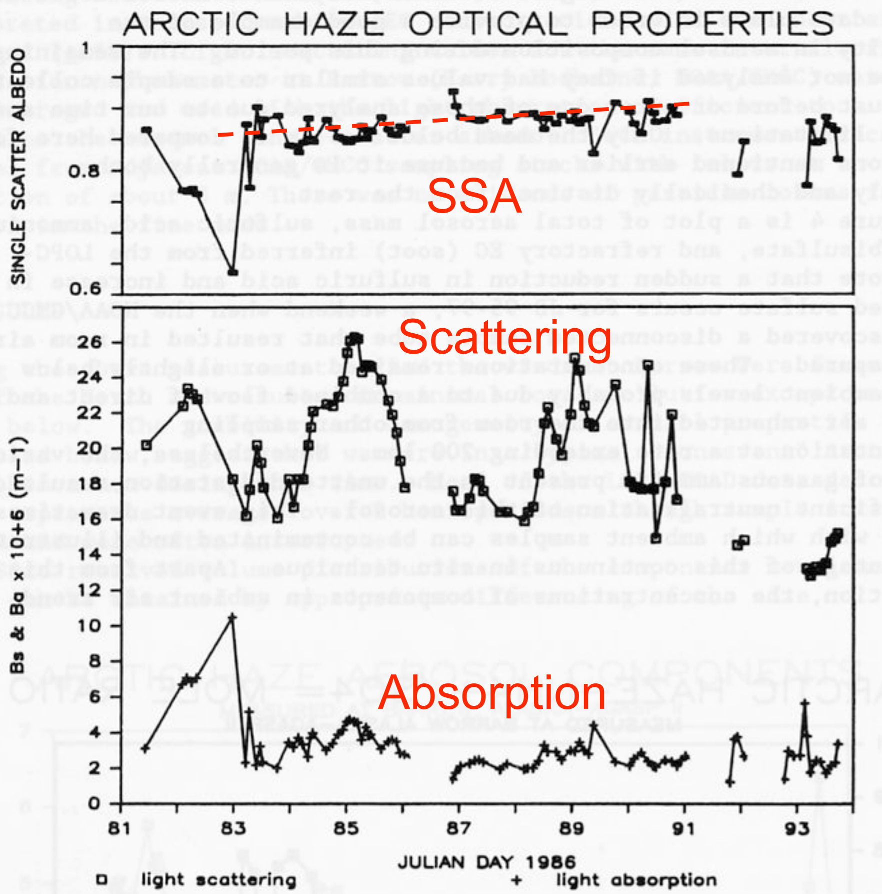

Figure 6. Time series of aerosol light-scattering (NOAA nephelometer), light-absorption (integrating sandwich) and the derived value of aerosol single scatter albedo. Local pollution clearly evident for JD 82-83.

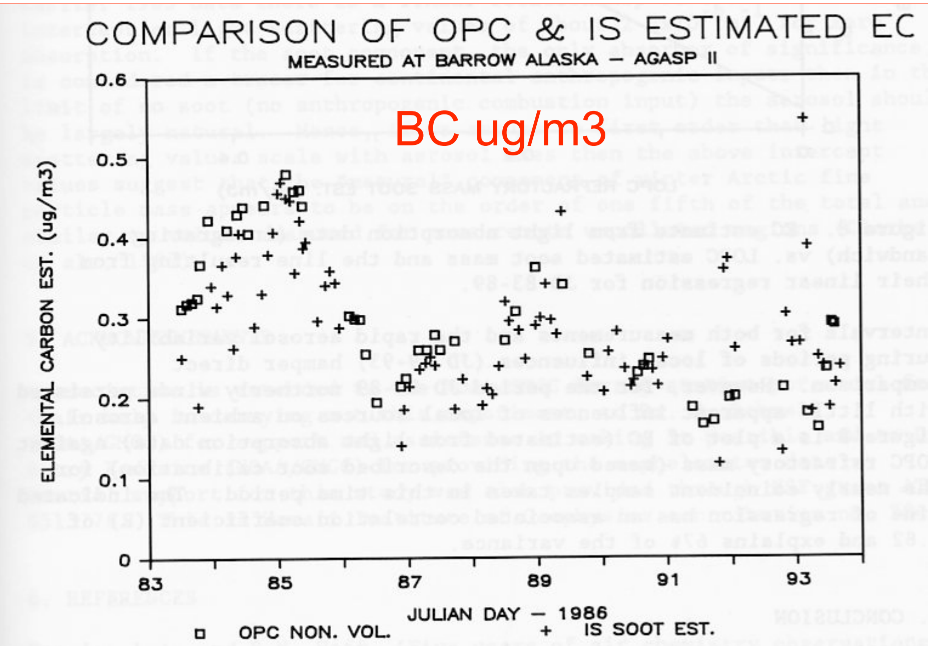

Figure 7. Time series of elemental carbon estimated from integrating sandwich light-absorption measurements compared to that inferred from the LOPC/TOAD refractory aerosol fraction.

Absorption & BC in April about 3 times higher than values in 2000, [Quinn report, 2005]

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Use of wavelength dependence of Absorption to separate Soot and Dust Absorption

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Soot filtered from snow from above tree-line

Dust from stream-flow above tree-line

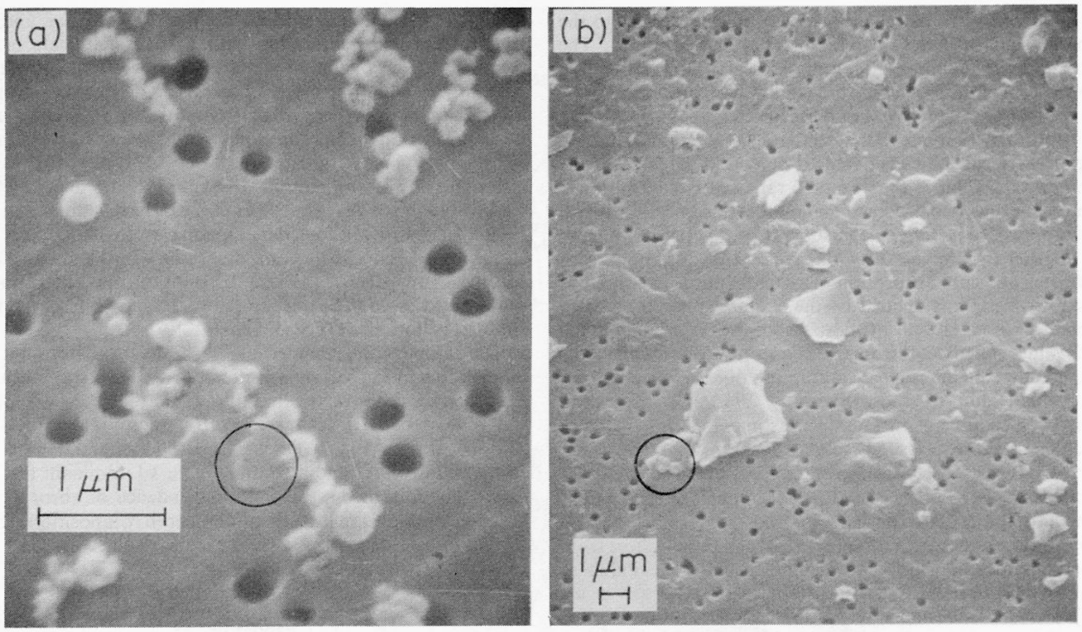

Fig. 3. Scanning electron photomicrographs of samples indicated in Fig. 2. (A) Snow extraction showing dominant soot particles and occasional crustal material (circled) and (B) river runoff of above treeline snowmelt showing locally derived crustal material and occasional soot particles (circled).

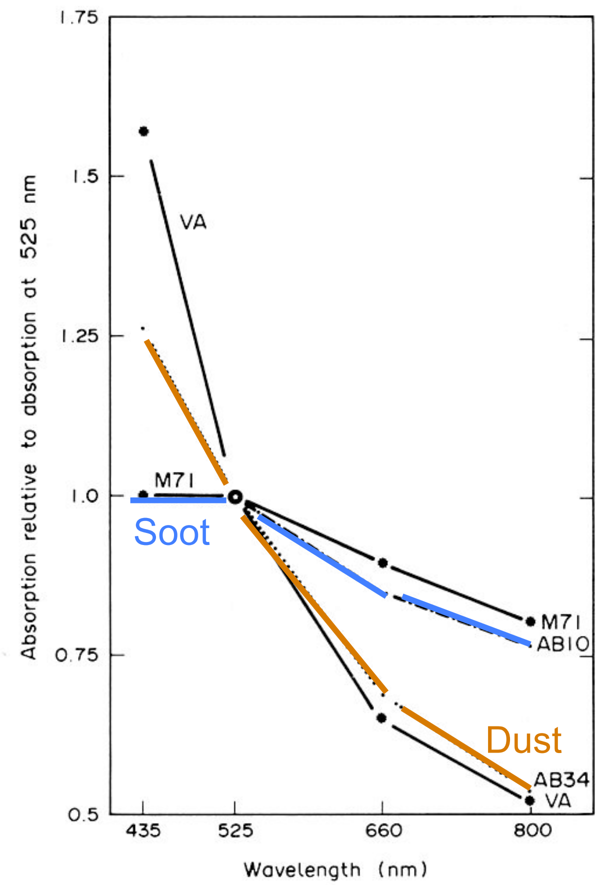

Fig. 2. Wavelength dependence of absorption ($\Delta I/I_0$) by filters of a fresh snow sample (AB10) and a river runoff sample (AB34) from above treeline in remote Sweden in comparison to that for calibration soot (M71) and volcanic ash (VA) from El Chichon (see Fig. 3).

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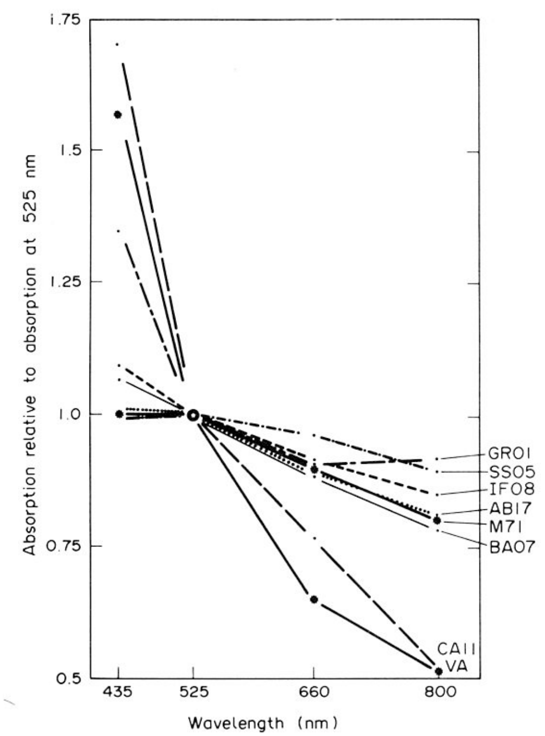

Fig. 4. Wavelength dependence of absorption $(\Delta I/I_0)$ normalized to absorption at 525 nm for examples from various Arctic locations (Table 1) in comparison to the EC reference M71 and El Chichon volcanic ash (VA).

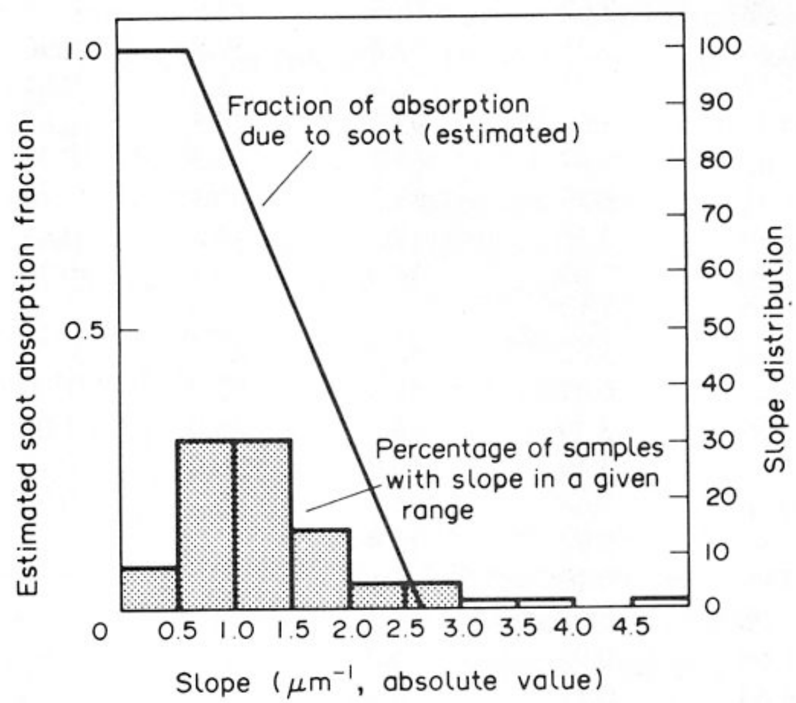

Fig. 5. Plot of estimated fraction of absorption due to soot and the frequency distribution of the measured slope (of normalized absorption between 535 and 660 nm) as a function of slope value.

BC in Snow from

BA – Barrow
CA – Canada
GR – Greenland
IF – Ice Floe
SS – Spitzbergen
AB- Abisko, Sweden
HH – Hurricane Hill (WA)

Greenland (4300 m alt.) BC was lowest at 2ng/g

Typical about 25ng/g

Albedo reduction expected at 1-3%

Table 1. Summary of sample data for Arctic snow collected in 1983 and 1984.

ID	Date	Snow code	pH	Cond. UMHO	Vol. (ml)	Slope	M71 ($\mu g\,cm^2$)	Max. EC ($ng\ g^{-1}$)	Est. EC ($ng\ g^{-1}$)	Est./Max.
BA01	830413	NF	6.10	2220.0	300	−1.29	2.89	20.6	13.5	0.66
BA02*	830413	NF	6.15	?	347	−2.25	1.00	6.2		
BA03	830413	WB	5.50	645.0	338	−0.85	4.42	28.0	24.5	0.87
BA04	830413	WB	5.50	366.0	308	−1.29	6.97	48.4	31.7	0.65
BA05	830413	WB	5.60	717.0	330	−0.98	2.84	18.4	14.9	0.81
BA06	830420	FR	5.50	195.0	180	−0.42	2.02	24.0	24.0	1.00
BA07	830420	WB	5.12	1110.0	253	−0.89	5.04	42.6	36.5	0.86
BA08	830420	FI	5.61	376.0	328	−0.88	2.78	18.1	15.6	0.86
BA09	830420	FI	5.51	229.0	333	−1.49	2.05	13.2	7.3	0.55
BA10	830420	FI	5.70	26.7	316	−1.48	3.22	21.8	12.2	0.56
BA11	830420	FR	4.80	182.0	180	−0.69	5.33	63.4	60.4	0.95
BA18*	840313	FR	5.19	12.7	153	−1.23	0.73	10.2		
BA19	840310	FI	6.50	1580.0	281	−1.43	2.60	19.8	11.5	0.58
CA01	831215	WB	5.90	8.3	173	−1.02	12.22	151.2	119.6	0.79
CA02	831111	FW	5.80	4.5	204	−0.97	8.88	93.2	76.0	0.82
CA03	831103	FR	6.30		72	−1.58	1.41	41.9	21.4	0.51
CA04	831103	NF	6.85	59.4	123	−1.63	9.24	160.8	78.1	0.49
CA07	831118	FW	6.80	6.8	84	−2.60	1.64	41.8	0.0	0.00
CA08*	831117	FR	6.12	4.0	150	0.09	0.92	13.1		
CA09	831102	NF	6.07	15.9	65	−1.61	7.83	257.8	127.0	0.49
CA11	831128	WB	5.80	4.4	194	−1.74	3.24	35.7	15.4	0.43
CA14	831210	FR	5.98	5.7	190	−1.76	3.66	41.2	17.3	0.42
GR01	830516	SP	5.92	3.08	290	−0.64	1.18	8.7	8.5	0.98
GR03	830516	SP	5.70	2.92	347	−1.80	1.74	10.7	4.3	0.40
GR05	830516	SP	5.67	2.59	326	−0.73	0.47	3.1		
GR07*	830516	SP	5.79	1.19	333	−3.26	0.18	1.2		
GR09*	830516	SP	5.80	1.32	312	−2.60	0.31	2.1		
GR12*	830423	FW	5.51	1.83	248	−1.98	0.72	6.2		
GR16*	830516	SP	5.97	56.90	295	−1.35	0.26	1.9		
GR19*	830516	SP	5.75	1.44	289	−1.12	0.26	1.9		
GR21*	830516	SP	5.59	1.59	300	−1.31	0.27	1.9		
IF01*	830715	FR	6.50	7.01	200	2.96	0.06	0.6		
IF02	830715	NF	6.18	8.27	306	−1.08	2.62	18.3	13.9	0.76
IF04	830715	NF	7.60	2.08	373	−0.68	9.21	52.8	50.8	0.96
IF05	830715	NF	6.80	2.51	447	−1.31	1.75	8.4	5.4	0.64
IF07	830717	FR	6.80	11.54	199	−0.98	8.67	93.2	75.5	0.81
IF08	830717	FI	6.00	11.45	303	−0.63	8.67	61.2	60.3	0.98
IF09	830717	FR	6.30	36.60	196	−1.01	5.79	63.2	50.3	0.80
IF11	830717	NF	6.30	2.25	452	−0.90	3.66	17.3	14.8	0.85
SS02	830507	FR	6.00	4.1	129	−2.20	2.03	34.0	6.7	0.20
SS03	830511	FR	5.62	5.4	212	−0.60	3.37	34.0	33.9	1.00
SS04	830508	FR	5.40	9.9	245	−1.20	3.52	30.7	21.5	0.70
SS05	830512	FW	6.10	13.8	250	−0.28	6.07	52.0	52.0	1.00
SS06	830504	FR	5.39	25.4	151	−0.60	3.39	48.0	48.0	1.00
SS07	830430	WB	5.20	6.0	250	−1.21	3.49	30.0	20.9	0.70
SS08	830430	WB	5.60	12.3	225	−0.68	3.68	35.0	33.5	0.96
SP01*	840225	FW	5.10	22.8	144	−1.81	0.92	23.4		
SP02*	840308	FR	5.25	6.5	86	−3.99	0.19	8.1		
SP03*	840308	FR	5.15	33.8	132	−2.08	0.63	17.5		
SP04*	840311	FR	4.70	8.3	96	−1.60	0.95	36.2		
SP05*	840221	FR	5.00	13.9	136	−4.83	0.17	4.60		
AB06	840328	FR	4.61	11.8	153	−0.66	0.95	45.5	44.1	0.97
AB07	840328	FR	4.80	11.1	160	−0.62	3.52	77.90	77.0	0.99
AB10	840330	FR	4.81	9.1	167	−1.26	0.60	13.20	8.8	0.67
AB11	840330	FR	4.70	10.7	100	−0.42	0.91	32.00	32.0	1.00
AB16	840409	FR	4.60	15.3	219	−0.27	2.25	36.60	36.6	1.00
AB17	840409	FR	4.65	10.7	119	−0.79	1.08	32.90	29.7	0.90
AB18	840413	FR	4.95	6.1	189	−1.06	0.72	13.20	10.2	0.77
AB19	840413	FR	4.82	8.3	183	−1.10	1.25	34.30	25.7	0.75
HH04	840329	NF	5.65	30.9	295	−1.32	3.32	24.1	15.4	0.64
HH07	840329	NF	5.61	24.3	309	−0.70	1.53	10.6	10.1	0.95
HH08	840329	FR	5.52	4.3	451	−0.64	3.99	18.9	18.5	0.98

*Low absorption, EC not estimated from slope.

The snow code refers to snow conditions, fresh (FR), non-fresh (NF), windblown (WB), fresh windblown (FW), firn (FI) and snow-pit (SP). The total sample absorption is expressed as equivalent surface concentration of M71 $\mu g\,cm^{-2}$ to get the maximum uncorrected mixing ratio of equivalent EC, MAX. EC (ng.g) which is then corrected using the slope of the wavelength dependence (see text) to get an estimated EC mixing ratio, EST. EC (ng.g). The last column is the fraction of the total absorption attributable to EC.

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Monthly Radiative Forcing for Snow Albedo Reduction compared to Artic Haze and Seasonal Integrated Effects for both

Table 2. Comparison of impacts of reduced snow albedo due to soot upon Arctic radiation budget during winter and spring months including similar calculations for atmospheric Arctic haze (after Cess)

Over Season

Irrad. (W m^{-2}) Forcing	Feb.	Mar.	Apr.	May	June	July	J m^{-2} $\times 10^7$
Q^* Top	5.0	89.0	243.0	415.0	—	—	—
ΔQ^* Top	1.8	7.5	14.0	8.2	—	—	8.19
ΔQ^* Surf.	−0.3	−3.0	−5.1	−3.8	—	—	−2.95
Q† W/Cloud	6.9	54.6	164.6	262.4	288.9	212.4	
ΔQ Snow	0.1	1.1	3.3	5.2	5.8	4.2	4.64‡
Q† Clear	6.9	56.2	195.2	321.8	400.3	370.2	
ΔQ Snow	0.1	1.1	3.9	6.4	8.0	7.4	6.06‡

*Data after Cess (1983) for atmospheric Arctic haze.
†Data after Fletcher (1965), Cloud (measured W/cloud), clear (ideal cloud free).
‡Based on snow cover for half of July only.

Net 5.24

Atmos. Haze Forcing Cess, 1983 >>>

Albedo Forcing Normal Cloud >>>

Albedo Forcing Ideal Clear >>>

About 3 times Flanner(2006, Fig. 6) est. for BC 1998-2001, consistent with higher emissions in 1983

Soot Scavenging Measurements for Arctic Snowfall
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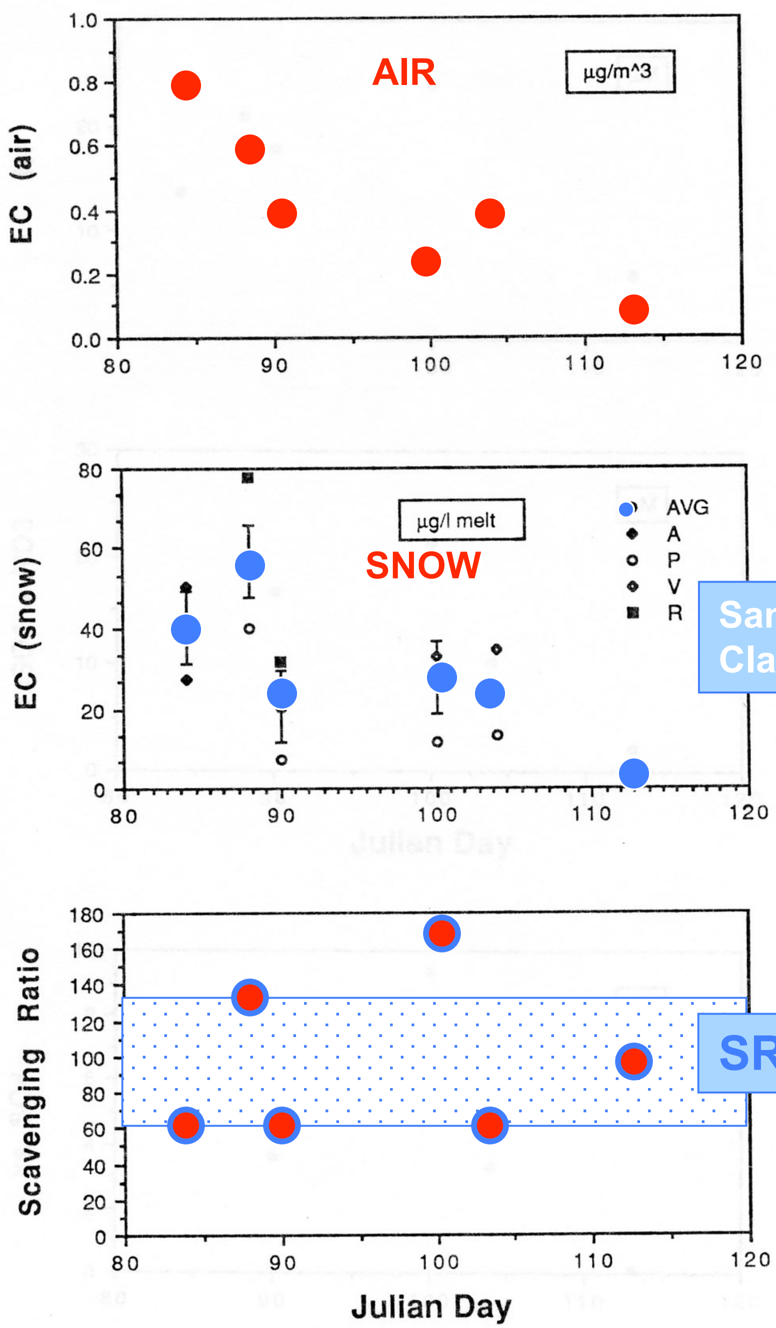
SCAVENGING RATIO
[ug BC/g$_{meltwater}$ / ug BC/g$_{air}$]

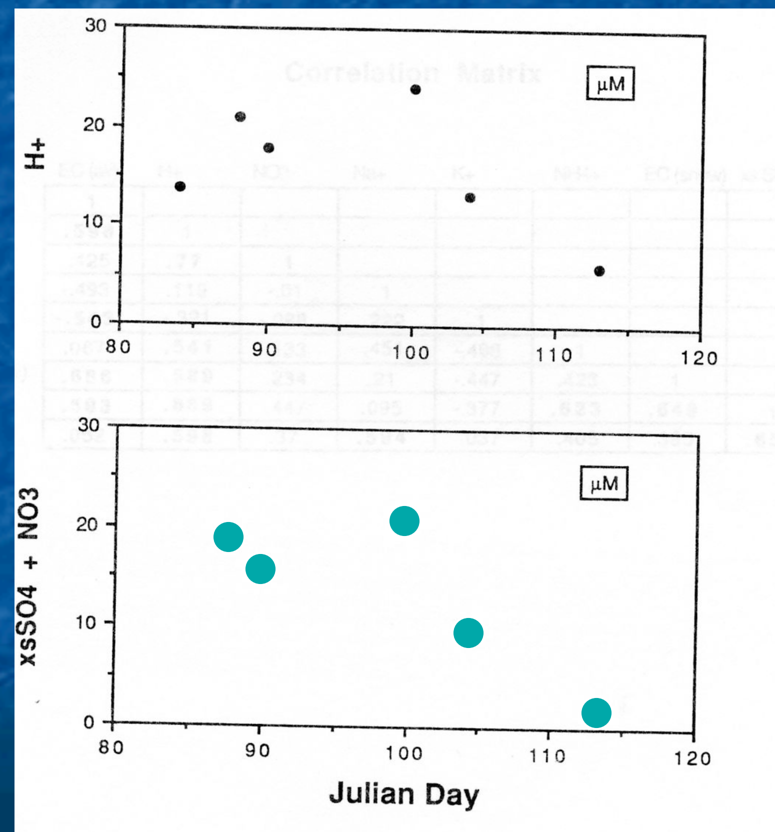
Abisko sampling 1984 (Six Storms)

A-Abiskosuolo (350m) P-Paktajakka (440m)
V-Vassijaure (650m) R-Riksgransen (600m)



Same range as Clarke & Noone

SR= 97 +/- 34



SR - SO4 here ~ 175
SR - SO4 Greenland, Davidson 1987 100-200

Summary for Early 1980's – March April

- Arctic Haze Absorption Range Typical 1-10 Mm-1 or 100 – 1000ng/m3 BC
- Single scatter albedo of haze (550nm) about 0.86 +/- 0.05
- Soot in snow was about 2 – 50 ng/g typical, 25ng/g avg.
- Albedo reduction due to BC estimated about 1-3%
- Seasonal Forcing in Snow equivalent to atmosphere and additive.
- Scavenging Ratio of Atmospheric Soot to Snowfall
  about 100 +/- 35 (limited data) -- [100 – 200 ?]
- Russia and North America major sources at Barrow 1983

Soot Scavenging Measurements for Arctic Snowfall

Noone, K. J., A. D. Clarke

Atmospheric Environment, 22, 12, 2773, 1988.

Table 1. Data set for the Abisko, 1984 sampling campaign

ID	Location	Julian day	Volume (ml melt)	Cond. ($\mu S\,cm^{-2}$)	pH	EC (air) ($\mu g\,m^{-3}$) (max.)	EC (air) ($\mu g\,m^{-3}$) (est.)	EC (snow) ($\mu g\,\ell^{-1}$ melt) (max.)	EC (snow) ($\mu g\,\ell^{-1}$ melt) (est.)	W.R.	Cl^{-}*	NO_3^- (μM)	SO_4^{2-} (μM)	Na^+ (μM)	K^+ (μM)	NH_4^+ (μM)	H^+ (μM)	xs SO_4^{2-} (μM)	$(\Sigma_+ - \Sigma_-)/E_\pm$
4	A	84	152	19.05	4.80	0.93	0.93	50.4	50.4	70.07							15.85		
6	P	88	153	11.80	4.61	0.70	0.70	45.4	44.0	81.27	18.24	11.51	13.20	15.66	0.92	11.97	24.55	12.26	−0.03
7	R	88	160	11.10	4.80	0.52	0.52	77.9	77.1	191.71	149.50	6.55	13.30	128.33	2.76	13.96	15.85	5.60	−0.06
10	P	90	167	9.10	4.81	0.21	0.21	13.2	8.8	54.18	89.19	14.41	5.10	76.56	10.14	5.98	15.49	0.51	−0.03
11	R	90	100	10.65	4.70	0.57	0.57	32.0	32.0	72.59	63.85	11.80	10.00	54.81	6.45	7.98	19.95	6.71	−0.03
16	P	100	219	15.30	4.60	0.29	0.27	36.6	36.6	175.27	164.20	14.62	18.26	140.94	1.84	19.94	25.12	9.80	−0.07
17	V	100	119	10.65	4.65	0.23	0.23	32.9	29.6	166.40	162.17	9.45	17.30	139.20	3.69	21.94	22.39	8.95	−0.05
18	P	104	189	6.10	4.95	0.44	0.42	13.2	10.2	31.40	14.70	9.39	0.70	12.62	0.03	11.97	11.22	−0.06	0.17
19	V	104	183	8.25	4.82	0.41	0.39	34.3	25.7	85.21	40.04	4.51	8.70	34.47	1.84	15.96	15.14	6.64	0.04
20	P	113	226	9.10	5.20	0.06	*0.06	3.8	*3.8	81.89	107.44	1.22	4.00	92.22	3.23	7.98	6.31	−1.53	−0.03
21	V	113	149	10.80	5.24	0.03	*0.03	2.4	*2.4	103.44	111.49	2.62	7.40	95.70	12.44	9.97	5.75	1.66	−0.02

—The location identification codes are A—Abiskosuolo, P—Paktajåkka, R—Riksgränsen, V—Vassijaure. Data were taken during March–April. The EC (air) and EC (snow) values delimited with an asterisk had absorption values too low for the correction procedure to be applied. For these values, it was assumed that all of the absorption was due to soot.

Correlation Matrix

	EC (air)	H+	NO3-	Na+	K+	NH4+	EC (snow)	xs SO4=
EC (air)	1							
H+	**.596**	1						
NO3-	.425	**.77**	1					
Na+	-.493	.119	-.01	1				
K+	**-.543**	-.391	-.088	.222	1			
NH4+	.067	**.541**	.133	.451	-.488	1		
EC (snow)	**.686**	**.589**	.234	.21	-.447	.423	1	
xs SO4=	**.593**	**.889**	.447	.095	-.377	**.623**	**.649**	1
Cond.	.052	**.598**	.37	**.594**	.037	.405	.395	**.653**